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The pitch drop experiment

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Abstract An account is given of an experiment, begun in 1927, to illustrate the fluidity of pitch.

Summarium Relatio experimenti picis fluiditatem ostendentis.

Introduction

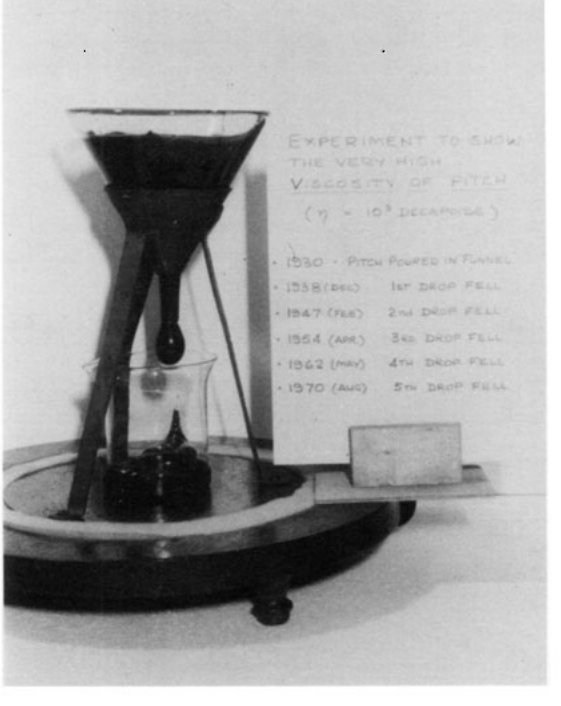
In the foyer of the Department of Physics at the University of Queensland in Brisbane is an experiment to illustrate, for teaching purposes, the fluidity and the very high viscosity of pitch, set up in 1927 by Professor Thomas Parnell, the first Professor of Physics there.

The pitch was warmed and poured into a glass funnel, with the bottom of the stem sealed. Three years were allowed for the pitch to consolidate, and in 1930 the sealed stem was cut. From that date the pitch has been allowed to flow out of the funnel and a record kept of the dates when drops fell. The observations which appear in the illustration are brought up to date in table 1. The pitch in its funnel is not kept under any special conditions, so its rate of flow varies with normal, seasonal changes in temperature.

An estimate can be made of the viscosity of pitch assuming that the flow through the stem (length l, diameter d) obeys Poiseuille's law as modified to take into account the weight of the pitch in the stem itself. As the volume of pitch in the funnel is relatively large, the pressure at the top of the stem of the funnel is assumed to be given by the hydrostatic expression $P_A + \rho g h$, where ρ is the density of pitch, h is the depth of pitch in the funnel and P_A is the atmospheric pressure. The pressure at the exit of the stem is taken to be P_A, thus ignoring for the present the possible change in the pressure at this point due to the formation of the pendant drop of pitch. With these assumptions the volume V of pitch that flows through the tube in time T is given by

$$\frac{V}{T} = \frac{\pi d^4 \rho g}{128\eta}\left(1 + \frac{h}{l}\right).$$

Figure 1 Apparatus for the pitch drop experiment showing the dates of each event. See also table 1.



† The text below was based on a letter to the editor of the *Brisbane Telegraph* written by RE in 1976 and supplemented by recent measurements made by BJD and RE.

‡ Professor Parnell (1880–1948) was responsible for setting up this experiment.

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The quantity $1/\eta$ really represents a time average of the inverse of the viscosity over the period in question.

Measurements of the various quantities yielded the following results: $h=(7.5\pm0.1)\times10^{-2}$ m, $l=(2.9\pm0.1)\times10^{-2}$ m, $d=(0.94\pm0.02)\times10^{-2}$ m. Unfortunately it was difficult to measure the internal diameter of the stem very accurately for fear of damaging the exhibit, and this alone limits significantly the final accuracy for the viscosity. The stem is also wider at the top (1.20×10^{-2} m) than at the bottom (0.94×10^{-2} m) and the latter value is chosen on the grounds that the narrowest diameter should be most important in determining the flow. Again to avoid damage, the volume of pitch that flowed through in the 582 months (approximately) from (about October) 1930 to April 1979 was obtained indirectly. This was done by measuring the mass of water needed to fill the beaker, into which the pitch drops fell, up to a convenient mark, and then (by measuring the dimensions of the beaker) determining the volume of water required to fill the beaker (if empty of pitch) up to the same mark. The difference in these two water volumes is the volume of pitch. We find that $V=(4.7\pm0.5)\times10^{-5}$ m^3 with $T=(1.530\pm0.006)\times10^9$ s. The density of pitch is 1.1×10^3 kg m^{-3} (Kaye and Laby 1973).

The viscosity of pitch is then calculated as $\eta=(2.3\pm0.5)\times10^8$ Pa s, which is enormous compared to that of common liquids—water at 20 °C has a viscosity of 1.0×10^{-3} Pa s. It should be noted however that (ignoring superfluidity) it is close to the geometric mean of the range of values that physicists consider—the effective viscosity of the Earth is of the order of 10^{20} Pa s (Stacey 1977).

The presence of the pendant drop implies that the pressure P_0 at the exit of the stem would differ from P_A. It is not obvious whether $P_0>P_A$ (as in a bubble) or whether $P_0<P_A$ (suction effect). Allowing for this adds a contribution $((P_A-P_0)/\rho gl)$ to the factor $(1+(h/l))$. This contribution is probably of order d/l, where d is the length of the pendant drop (which could be about 20 mm when the drop is about to fall) and hence has a magnitude of ~0.6, therefore a further uncertainty in viscosity of about 50 per cent follows.

Table 1 Record of pitch drops.

Year	Event
1930	The stem was cut
1938 (Dec)	1st drop fell
1947 (Feb)	2nd drop fell
1954 (Apr)	3rd drop fell
1962 (May)	4th drop fell
1970 (Aug)	5th drop fell
1979 (Apr)	6th drop fell

Results for the viscosity of pitch at various temperatures are reproduced in both tabular and graphical form in the book by Hatschek (1928) based on the measurements of Pochettino (1914). It is not known of course whether this type of pitch is the same as in the pitch drop experiment. The viscosity of pitch varies enormously with temperature, being 2.35×10^9 Pa s at 9.0 °C (corresponding to the lowest average minimum daily temperature in Brisbane, which occurs in July) and 7.30×10^5 Pa s at 29.8 °C (corresponding to the highest average maximum daily temperature in Brisbane, which occurs in January). The value of viscosity from the pitch drop experiment certainly falls in this range.

As indicated previously the pitch drop experiment is not kept in a temperature controlled environment and estimations of the actual temperature changes from 1927 to the present time involve a lot of guesswork. Nevertheless even allowing for the likelihood of the pitch being a different type it may be of interest to see whether reasonably plausible models of the temperature changes combined with Pochettino's (1914) viscosity measurements would yield a value for the average value of $1/\eta$ that is roughly in accord with the result from the pitch drop experiment. From the diffusion equation the characteristic time for relaxation of a temperature profile is of order $(a^2\rho C)/K$, where a is the size of the system, C the specific heat and K the thermal conductivity. Assuming that C is of order 3×10^3 J kg^{-1} °K^{-1} (as for paraffin wax (Kaye and Laby 1973) K is of order 0.17 Wm^{-1} K^{-1} (as for bitumen (Kaye and Laby 1973) then with $a\sim1$ cm the temperature relaxation time is about 0.7 h. The relaxation time for the glass in the stem ($a\sim1$ mm) is even shorter. Thus the pitch in the stem of the funnel would probably follow the day-night temperature variations. The average daily minimum and maximum

Table 2 Average daily maximum and minimum temperatures, Brisbane.

Month	Average daily minimum (°C)	Average daily maximum (°C)	Average daily temperature (°C)
January	20.7	29.4	25.0
February	20.5	29.0	24.7
March	19.3	27.9	23.6
April	16.6	26.1	21.6
May	13.3	23.2	18.2
June	10.8	20.9	15.8
July	9.5	20.4	14.9
August	10.3	21.8	16.0
September	12.8	24.0	18.4
October	15.7	26.1	20.9
November	18.1	27.8	22.9
December	19.8	29.1	24.4

Table 3 Various temperature models and calculated value of viscosity.

Model	Features	Calculated value of viscosity (Pa s)
I	Daily and monthly temperature variations as in table 1.	7.96×10^6
II	No daily temperature fluctuations. The monthly temperature variation follows the daily average given in table 1.	1.50×10^7
III	The monthly temperature variation follows the daily average given in table 1. The daily temperature fluctuation is ±2 °C (+day, −night).	1.28×10^7
IV	No daily temperature fluctuations. The monthly temperature varies from 1 °C warmer (summer) to 2 °C warmer (winter) than for the daily average given in table 1.	8.76×10^6
V	The monthly temperature variation is as in model IV. The daily temperature fluctuation is ±2 °C (+day, −night).	7.65×10^6
VI	No daily temperature fluctuations. The monthly temperature varies from 4 °C cooler (winter) to 7 °C cooler (summer) than for the daily average given in table 1.	2.21×10^8
VII	The monthly temperature variation is as in model VI. The daily temperature fluctuation is ±2 °C (+day, −night).	1.93×10^8

temperatures measured at the Brisbane Weather Bureau are listed in table 2. Various temperature models (which are listed in table 3) have been considered, with daily temperature fluctuations assumed to be sinusoidal. The calculated values for the viscosity, obtained by numerically averaging $1/\eta$ using a computer, are also stated. We note that including daily temperature fluctuations results in a lower viscosity than if they are ignored, the high temperature swing, which lowers the average viscosity, more than compensates for the low temperature swing that increases it. Given that the exhibit has been housed in a large building it is probably realistic to assume daily temperature fluctuations of ±2 °C rather than the ±5 °C applying for the outside air. However, the average daily temperature inside the building is probably about 1 °C warmer than the outside air in summer and about 2 °C warmer than outside in winter due to energy inputs from the occupants, electrical apparatus etc. located inside the otherwise unheated building (having no air-conditioning). Thus model V is probably the most realistic model. However the calculated value for the viscosity (7.7×10^6 Pa s) in this model is still a factor of thirty lower than the pitch drop result (2.3×10^8 Pa s). Model VI with no daily temperature fluctuations and with an average daily temperature between 6 °C and 8 °C cooler than for model V is in closest agreement but is a rather implausible model. Allowing the pitch drop result to be as low as 1×10^8 Pa s due to the possible effect of the pendant drop brings model VII into agreement with the experimental result. However even though this model includes realistic daily temperature fluctuations, its average daily temperature variation is still implausible.

Thus the result for the viscosity from the pitch drop experiment does not agree well with the predictions based on Pochettino's measurements (Pochettino 1914), even allowing for the enormous variation of viscosity with temperature and the rather unknown temperature history of the experiment. The probable explanation lies in the differing viscosities of different samples of pitch—these could have dissimilar proportions of trapped volatile hydrocarbons and this would affect the viscosity.

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